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Analysis of Some Crude Main Injector Radiation Cool-down Data

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Abstract

In order to plan for radiation exposure during work in the accelerator tunnels, one needs to have exposure estimates which include an estimate of the expected cool-down in the area where work will take place. In order to gain some understanding of this process, some data was acquired for the MI52 area. Data was recorded for 68 days during the 2007 Fermilab Facility Shutdown (Aug - October) and for 18 hours during a maintenance period in July 2008. This work compares the fraction of short lived and long lived components for these measurements and finds systematic differences which correlate with the distance to the major loss points. Related measurements near MI105 and MI402 will be made available. The data will be provided in the associated spreadsheet for this document in addition to this summary of results.

1 Introduction

Monitoring of the loss patterns in the Main Injector has been less aggressively studied than was the case for the Booster. They could tour the tunnel much more quickly and the issues are believed to have been more serious so they were granted a measurement each week with tunnel entry achieved at a regular time after beam off. Since the Residual Radiation Tunnel Tour for Main Injector is about a two hour investment and since entry requires that anti-protons be dumped from the Recycler, the available data is much more sparse and the time between beam off and measurement considerably more variable. In an attempt to put some bounds on how important this might be, a cool-down study was carried out during the facility shutdown in 2007. This study was severely restricted for short-lived isotopes by a multi-day operating period of reduced intensity and a 2.5 day delay in first access. As concerns about construction at MI10 and MI40 for ANU upgrades grew, it was decided to do cool-down studies in a one day shutdown on July 17, 2008. Peter Kasper and Dave Capista carried out studies directly relevant to the ANU Project [1]. This work will emphasize studies carried out by the author primarily at MI52 but will report briefly on 2007 Facility Shutdown data from other interesting locations.

The tool for these studies was the ROTEM RAM DA-3 2000 Meter used for routine monitoring[2]. Guan Wu has provided application program I128 for storing and viewing the routine monitoring data. The meter has two Geiger counter detectors to provide very wide ranges of precise readings. The radiation measurements, time, and a bar code value to identify the location are stored in on-board memory and read out to a PC. Due to troubles in reading the bar code and/or operator error, some readings are missing.

2 Monitor Locations

During the 2007 Facility Shutdown, locations which are quickly accessible from the MI60 access point were chosen for the cool-down study. Five measurements at each of seven locations were planned in addition to 4 complete measurements at the approximately 126 bar coded locations which are repeatedly monitored around the ring (the regular monitoring now includes additional locations associated with the MI300 Collimator System). Four locations on Lambertson magnets and three other tunnel locations were selected. The same locations were chosen for the one day shutdown but additional measurements along the Lambertson magnets were measured.

3 Analysis Plan

The analysis goal is to establish some limits for the range of variability in cool-down rates to be expected in a limited number of locations. It was known beforehand that this sparse data would provide limited knowledge of the lifetimes and therefore of the cool-down rates. We will explore our ability to establish the ratio of long lived to short lived components with only a handful of measurements. We find it necessary to assume that two or three components dominate the measurements.

Let us assume that for each location we measure a rate R_N at each of several times, T_N. We will explore the compatibility of this with intensities I_a, I_b, I_c where these are the rate at beam off due to isotope a, b, c at the measured location. Initially, we will explore using particular isotopes with known half lives, $\tau_a < \tau_b < \tau_c$. With such sparse data, we are limited to assuming the first and last measurements are correct and employing them to set the parameters of the model. With them we set a ratio of short life over long life components (or short life over total). We will explore graphically the result for other measurements. When forced to a three component model, we will simply compare the predictions to the data graphically and adjust the ratio of the short life components manually. The results will be crude but the limitations will be apparent.

Let us establish the algebraic relations:

$$R(T) = I_a 2^{-T/\tau_a} + I_b 2^{-T/\tau_b} + I_c 2^{-T/\tau_c}. \tag{1}$$

At the first measurement time, T_1

$$R(T_1) = I_a 2^{-T_1/\tau_a} + I_b 2^{-T_1/\tau_b} + I_c 2^{-T_1/\tau_c}. \tag{2}$$

while at the last measurement time, T_N

$$R(T_N) = I_a 2^{-T_N/\tau_a} + I_b 2^{-T_N/\tau_b} + I_c 2^{-T_N/\tau_c}. \tag{3}$$

3.1 Two Component Formulas

For the long shutdown data, we assume that components I_a and I_b dominate and that both show significant decay during the measurement period. Taking the difference Eq. 2 minus Eq. 3 we find

$$R(T_1) - R(T_N) = I_a(2^{-T_1/\tau_a} - 2^{-T_N/\tau_a}) + I_b(2^{-T_1/\tau_b} - 2^{-T_N/\tau_b}) \tag{4}$$

Solving for initial rate I_a, we have

$$I_a = \frac{R(T_1) - R(T_N)}{(2^{-T_1/\tau_a} - 2^{-T_N/\tau_a})} - I_b \frac{(2^{-T_1/\tau_b} - 2^{-T_N/\tau_b})}{(2^{-T_1/\tau_a} - 2^{-T_N/\tau_a})} \tag{5}$$

but from Eq 3 we have

$$I_b = R(T_N)\frac{1}{2^{-T_N/\tau_b}} - I_a \frac{2^{-T_N/\tau_a}}{2^{-T_N/\tau_b}} \tag{6}$$

$$I_a = \frac{R(T_1) - R(T_N)}{(2^{-T_1/\tau_a} - 2^{-T_N/\tau_a})} - (R(T_N)\frac{1}{2^{-T_N/\tau_b}} - I_a \frac{2^{-T_N/\tau_a}}{2^{-T_N/\tau_b}}) \frac{(2^{-T_1/\tau_b} - 2^{-T_N/\tau_b})}{(2^{-T_1/\tau_a} - 2^{-T_N/\tau_a})} \tag{7}$$

$$I_a = (\frac{R(T_1) - R(T_N)}{(2^{-T_1/\tau_a} - 2^{-T_N/\tau_a})} - R(T_N)\frac{1}{2^{-T_N/\tau_b}} \frac{(2^{-T_1/\tau_b} - 2^{-T_N/\tau_b})}{(2^{-T_1/\tau_a} - 2^{-T_N/\tau_a})})/(1 - \frac{2^{-T_N/\tau_a}}{2^{-T_N/\tau_b}} \frac{(2^{-T_1/\tau_b} - 2^{-T_N/\tau_b})}{(2^{-T_1/\tau_a} - 2^{-T_N/\tau_a})}) \tag{8}$$

One will find that the denominator in this formula is very, very near 1 (for the data set acquired during the 2007 shutdown). We will use Eq. 8, then Eq. 6 to set the parameters and plug them into Eq. 1.

3.2 Three Component Formulas

For three components, we will, at best, be assuming a ratio of the two shorter-lived components fixed at a single value for all locations:

$$I_b = \alpha I_a \tag{9}$$

$$R(T) = I_a(2^{-T/\tau_a} + \alpha 2^{-T/\tau_b}) + I_c 2^{-T/\tau_c}. \tag{10}$$

Subtracting Eq. 3 from Eq. 2 we have

$$R(T_1) - R(T_N) = I_a((2^{-T_1/\tau_a} - 2^{-T_N/\tau_a}) + \alpha(2^{-T_1/\tau_b} - 2^{-T_N/\tau_b})) + I_c(2^{-T_1/\tau_c} - 2^{-T_N/\tau_c}) \tag{11}$$

For compactness, let us define d_S and d_L for the decay terms

$$d_S = (2^{-T_1/\tau_a} - 2^{-T_N/\tau_a}) + \alpha(2^{-T_1/\tau_b} - 2^{-T_N/\tau_b}) \tag{12}$$

$$d_L = (2^{-T_1/\tau_c} - 2^{-T_N/\tau_c}) \tag{13}$$

Solving for I_a and substituting, we have,

$$I_a = \frac{R(T_1) - R(T_N)}{d_S} - I_c \frac{d_L}{d_S} \tag{14}$$

again from Eq 3 we have

$$I_c = R(T_N)\frac{1}{2^{-T_N/\tau_c}} - I_a \frac{(2^{-T_N/\tau_a} + \alpha 2^{-T_N/\tau_b})}{2^{-T_N/\tau_c}} \tag{15}$$

Substituting I_c from Eq. 15 into Eq. 14 we have

$$I_a = \frac{R(T_1) - R(T_N)}{d_S} - R(T_N)\frac{1}{2^{-T_N/\tau_c}}\frac{d_L}{d_S} + I_a \frac{(2^{-T_N/\tau_a} + \alpha 2^{-T_N/\tau_b})}{2^{-T_N/\tau_c}}\frac{d_L}{d_S} \tag{16}$$

Re-solving for I_a, we have

$$I_a = (\frac{R(T_1) - R(T_N)}{d_S} - R(T_N)\frac{1}{2^{-T_N/\tau_c}}\frac{d_L}{d_S})/(1 - \frac{(2^{-T_N/\tau_a} + \alpha 2^{-T_N/\tau_b})}{2^{-T_N/\tau_c}}\frac{d_L}{d_S}) \tag{17}$$

As above for two components, we will employ Eq. 17 then Eq. 15 and of course, Eq. 9.

3.3 Relevant Isotopes

The list of possible isotopes is extensive, less so for relevant half lives, but still more than can be compared to this data set. We will restrict our attention to ones which are considered by Kasper [1].These are shown in Table 1

Table 1: Isotopes and Half Lives (values from Wikipedia)

Isotope	**Half Life**
^{54}Mn	312.3 days
^{52}Mn	5.591 days
^{52}Fe	8.275 hours
^{56}Mn	2.5789 hours

4 2007 Shutdown Data – 68 Days

There was a Fermilab Facility Shutdown in Fall 2007. Beam was turned off for the Main Injector at 8/5/2007 1:02. The first cool-down data was recorded at 8/7/2007 13:01 and the last radiation measurements for this study were taken on 10/12/2007 15:40. Short life radiation sources could not be studied both because of the 2.5 day delay before first measurements but also because of reduced beam intensities for many days prior to the shutdown. Ring-wide radiation surveys[2] were conducted on 4 occasions and additional cool-down measurements taken at the 7 locations in this study on 5 additional days. The data is displayed in Figures 1 and 2. Since the range of residual radiation levels is large (see Figure 4) we normalize to the initial radiation level (of the multi-day and longer components) using the two component model defined above. We assume that the slowly decaying component is ^{54}Mn (half life 312.3 days) and one short life component - ^{52}Mn (half life 5.591 days). To guide the eye, we plot the cool-down prediction for the initial fraction of the short lived component of 0.2, 0.3, 0.4, and 0.5. After 68 days, 86% of ^{54}Mn will remain. In addition to the 7 locations for which 9 measurements were recorded, we show also additional locations in MI52, MI10, and MI40 from the ring-wide surveys which are of particular interest at this time [1].

Only very advanced statistical measures of data quality could be useful for such data (we will not try) so the reader is encouraged to examine the graphs to gain confidence that the two component model is useful in describing the data. We will draw our tentative conclusions based on this assumption, *i.e.* the shape of the curves, but they will be valid to the extent the data is well described, whether or not more or different components are actually present. It is apparent that the various locations have quite different fractions of short life radiation sources. We comment that the data from locations with lower residual radiation usually show more scatter in the measurement results.

5 July 17, 2008 Cool-down Data - 18 Hours

The cool-down study authorized for the planned 2009 construction and reported in Kasper [1] provided an opportunity to extend the above studies to shorter lived components. On July 17, beam was off at 5:34 AM and measurements were carried out after about 1.5, 3.2, 8 and 17.6 hours. The seven locations studied during the 2007 Facility Shutdown were measured as well as the adjacent locations on LAM52A and LAM52B. The data is displayed in Figure 3. We normalize to the initial radiation level using the three component model defined above. We assume that the long lived component does not decay (a component with half life of 5.591 days only decays by 9%) and take for short lived components the two used by Kasper [1]: ^{52}Fe (8.275 hours) and ^{56}Mn (2.5789 hours). We plot the cool-down prediction for the initial fraction of the short lived component of 0.2, 0.25, 0.3, and 0.4. We have varied the share of the 8.275 hour component while examining the graphs and conclude that it is likely to lie in the region of $0.1 < \alpha < .25$ but fractions from negligible to 0.5 cannot be excluded by the data. The graphs use $\alpha = 0.1$. While α is probably a bit different in various locations, when using only one value, the ability to represent this data with the three component model is adequate to match the data quality. Clearly this data has more issues. We believe, however, that one can still predict a range of expected cool down parameters by examining these measurements.

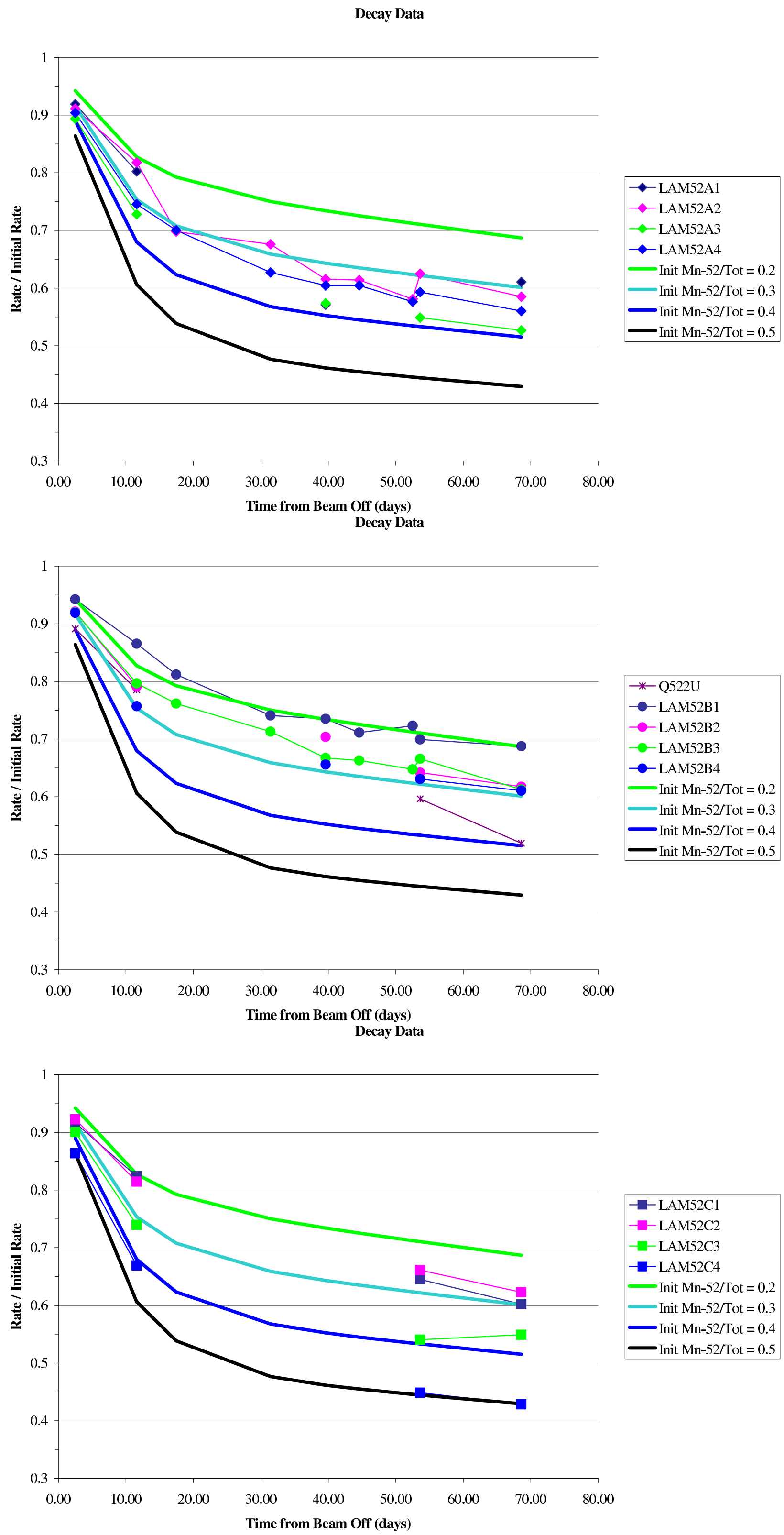

Figure 1: 68 Day Cool down Measurement at LAM52. Top: LAM52A, Middle: LAM52B Bottom: LAM52C

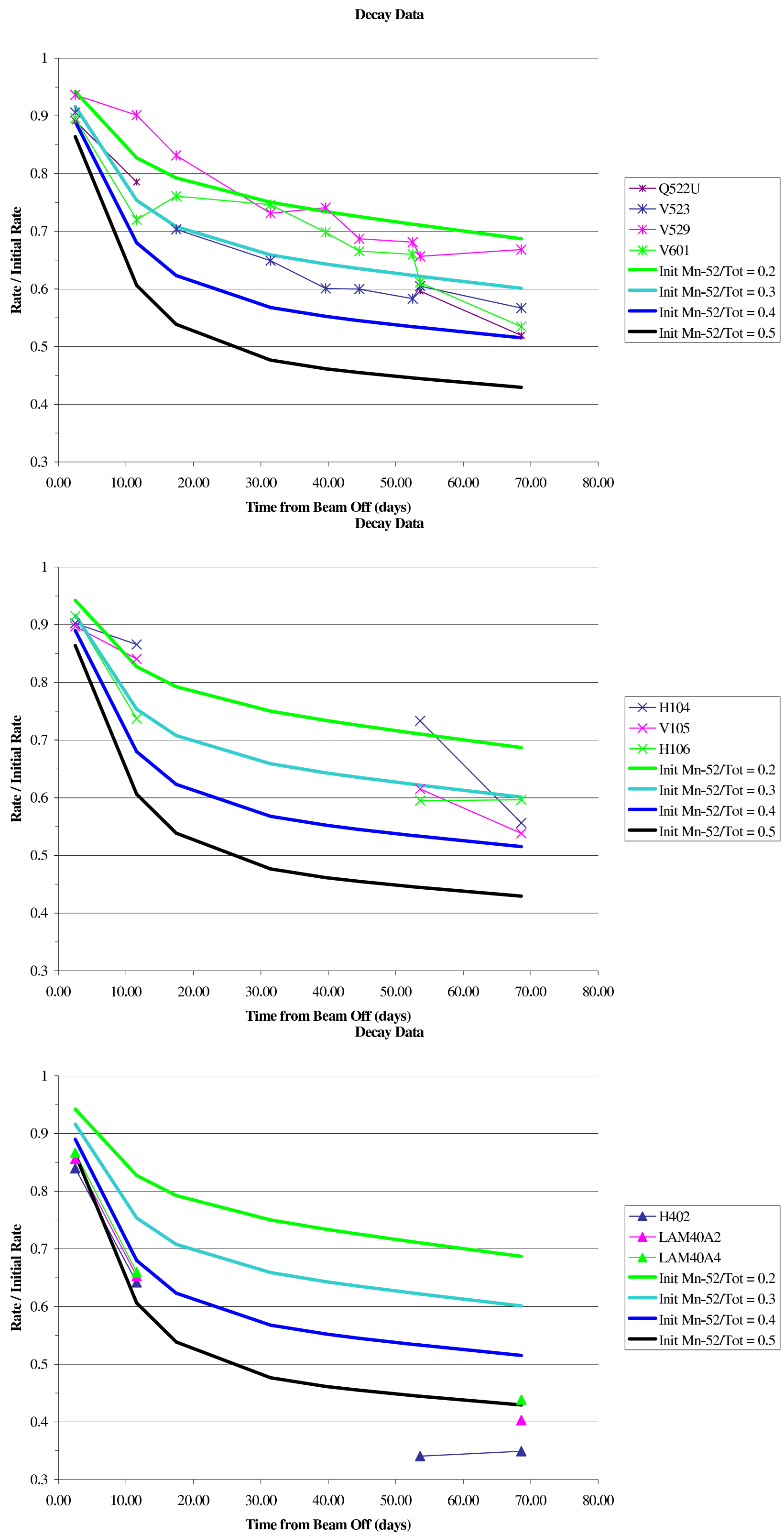

Figure 2: 68 Day Cool-down Measurement at V523,V529,V601 (top) from the cool-down study effort, at H104,V105,H106 (middle), and at H402, LAM40A2 and LAM40A4 (bottom). The additional measurements we not carried out in MI100 and MI400.

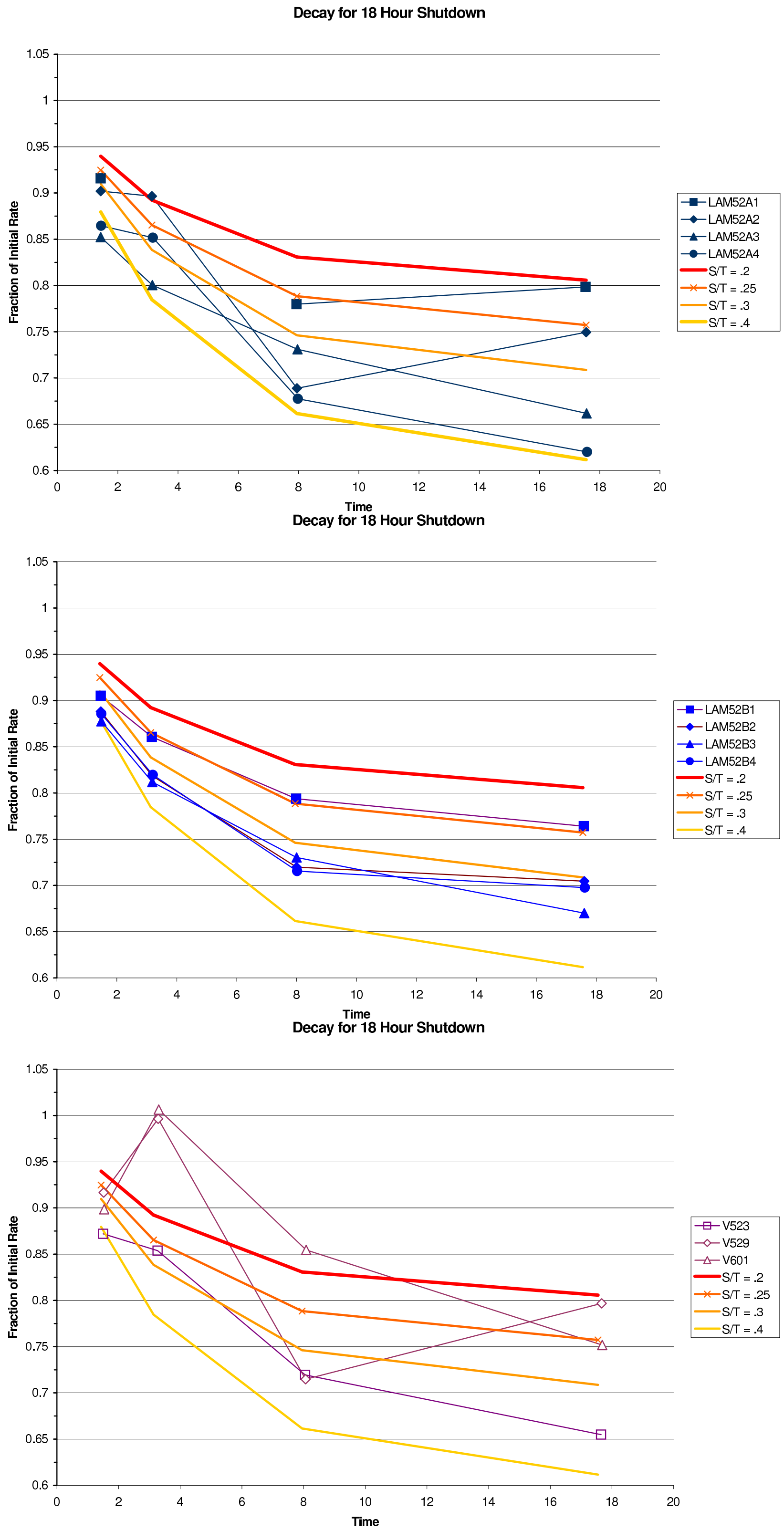

Figure 3: 18 Hour Cool-down Measurement at LAM52 area. Top: LAM52A, Middle: LAM52B Bottom: V523, V529, V601.

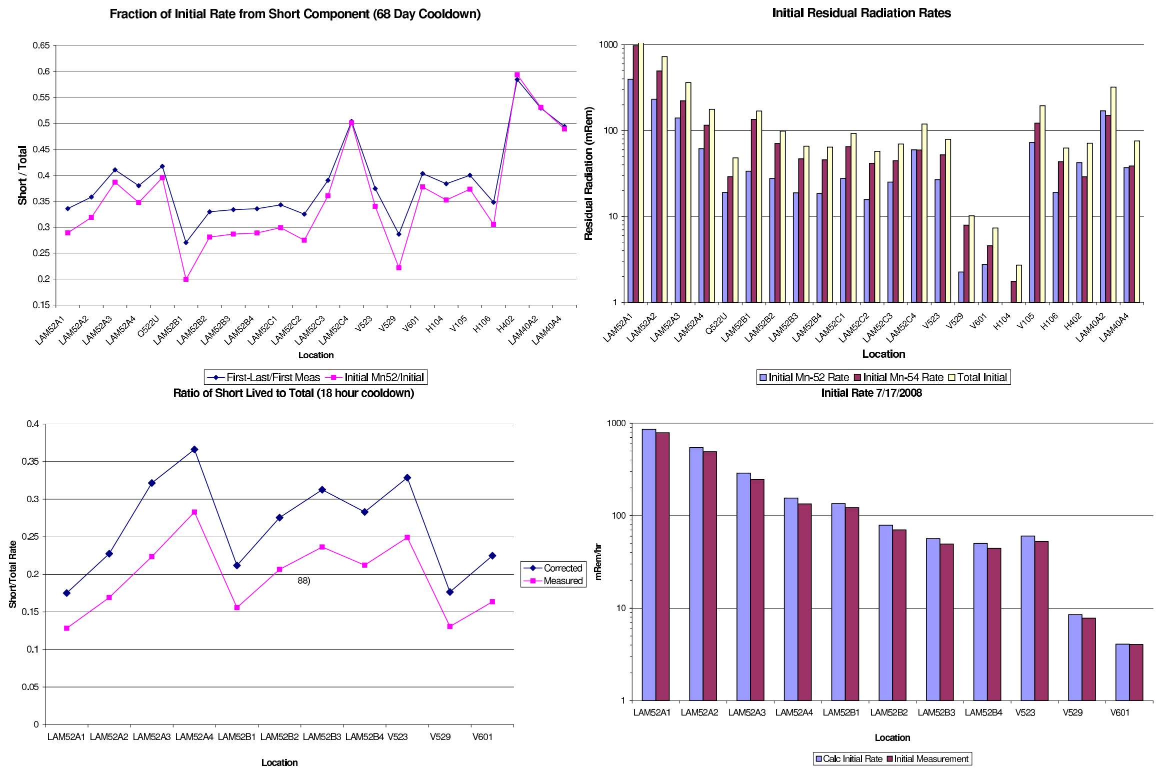

Figure 4: Results of analysis using first and last cool-down measurements. The upper plots are for the 2007 Shutdown (68 days). Lower plots are for July 17 study (18 hours). The intensities are shown on the right. On the left we plot the fraction of the initial rate contributed by one (upper) or two (lower) short-life components. To preserve visibility on the plot, the total initial rate at LAM52A is cutoff but can be inferred from the two components.

6 Analysis of Component Ratios

Since we conclude from the above data presentation that the analysis using two components or three components is useful, we will proceed to present the measurement results based on that analysis. In Figure 4 we show the intensities (right) and the fraction of short-life isotopes (left). The upper curves are for the 2007 Shutdown (68 days) while the lower figures are for the 18 hours study in July 2008. The measured result is the difference of first minus last measurement divided by the first measurement. This is corrected for the assumed lifetimes to get the ratio at beam off. Since the long lifetime component decays significantly during the 68 day measurement, the correction decreases the ratio whereas for the 18 hour data, the correction increases the short life fraction. Also note that the color choice reverses for the measured and corrected data in the two studies.

Most beam lost at MI52 strikes the upstream end of LAM52A and induces a hadronic shower which propagates along the magnet. Residual activation is induced by energetic hadrons (GeV) in the main shower (spallation), by fast neutrons (MeV) produced by those hadrons and by slow neutrons (<eV) which propagate further. These activation mechanisms produce isotopes with characteristically different residual radiation lifetimes. The residual radiation pattern falls almost exponentially as would be expected from hadronic shower characteristics (the scale for exponential fall is modified from that for a solid absorber by the half-open geometry of the magnet aperture). Of interest is the pattern shown for the fraction of short-life components. We display this both from

the two (three) component model and directly from the data. It is apparent that the upstream end of LAM52A shows a markedly smaller fraction of short-life components than the downstream end. The pattern is repeated in LAM52B. If no primary beam interacted at the upstream end of LAM52B, we would expect the trend to high short lifetime fraction to continue. But the log plot of residual radiation seems to indicate that some primary beam strikes the upstream end of LAM52B. (The reader needs be careful to note that the data on the bottom graphs includes only data from MI520 - MI601 whereas the top graph also shows analysis for measurements in MI100 and MI400.)

The variation by a factor of two of the short-life fraction inspired the effort required to present this data. Variations from place to place around the ring can be impacted by the accelerated intensities and loss history on the relevant time scales. However, we assert that the losses at LAM52 are alway dominated by the same loss pattern so an explanation for the changes is short-life ratio along the magnet should be sought. An explanation can be offered in terms of the fraction of activation by the GeV, MeV and eV components. The spallation process tends to produce longer life Isotopes. We are considering how to provide simulations for comparison.

7 Discussion

It is apparent that the cool-down of the Main Injector tunnel components varies from location to location. In planning for facility shutdown periods of 10 to 15 weeks, characteristic of the last decade of Fermilab operation, one knows that long-life Isotopes limit the cooldown which can be expected. The assumption that ^{54}Mn (half life312.3 days) can represent that limit seems adequate for the data examined. With short cool-down studies of a day or so, one can estimate the fraction of components with a few hour life time and this can be used to correct (or at least set limits on the uncertainty of) the measurements taken when the beam has been off for only a few hours. We see from the measurements during the 2007 Facility Shutdown that the fraction of long life can vary from 20% to 50% in the MI52 area. This analysis indicates that the ratio is about 35% in the injection area. The very high short fraction found for MI40 (up to 60%) may be real but one would want to consider that losses during the last days of operation might have been different from the rest of the ring in the Abort area.

8 Next Steps and Conclusions

For steady operation and steady loss rates, we should expect equilibrium production *vs.* decay for all components up to a few days. If we can measure cool-down curves, we can correct the measurements for short life components and detemine the build-up of long life components.

The BLM system in conjunction with the datalogger can provide the losses *vs.* time. As we understand the relation between losses and residual radiation, we should convolute the loss results over time with the various model life times to derive driving terms for the various components.

One can use the MARS code and a model of beam loss on the Lambertson to examine the expected isotopes and compare them to the cooldown curves. One could provide activation samples which one would expose for a defined period prior to removing them and measuring the various isotopic components in order to further constrain ones understanding.

Meanwhile, this data should permit rough estimates of the cooling expected for various regions of the tunnel. One could examine more of the 2007 Shutdown measurements to look for further patterns.

9 Acknowledgments

Assistance from Denton Morris and Dave Capista for acquiring this data is much appreciated. Discussions with Nikolai Mokhov, Igor Rakhno and others have encouraged this presentation.

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